Comparisons of soil suction induced by evapotranspiration and transpiration of S. heptaphylla

Garg, A.; Leung, A. K.; Ng, C. W. W.

Published in:
Canadian Geotechnical Journal

DOI:
10.1139/cgj-2014-0425

Publication date:
2015

Comparisons of soil suction induced by evapotranspiration and transpiration of S. *heptaphylla*

*A. Garg, A. K. Leung and C. W. W. Ng

Name: Dr Ankit, GARG* (Corresponding author)
Title: Visiting Research Scholar
Affiliation: Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology
Address: Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong
E-mail: agarg@ust.hk, **Telephone**: +852-23587169, **Fax**: +852-2358 1534

Name: Dr Anthony Kwan, LEUNG
Title: Lecturer
Affiliation: Division of Civil Engineering, University of Dundee, Scotland, UK
Address: Fulton Building, Division of Civil Engineering, University of Dundee, Nethergate, UK, DD1 4HN

Name: Dr Charles Wang Wai, NG
Title: Chair Professor of Civil and Environmental Engineering
Affiliation: Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology
Address: Department of Civil and Environmental Engineering, Hong Kong University of Science and Technology, Clear Water Bay, Kowloon, Hong Kong

---

Comparisons of soil suction induced by evapotranspiration and transpiration of S. *heptaphylla*

ABSTRACT

For a given evapotranspiration (ETr), both soil evaporation and plant transpiration (Tr) would induce soil suction. However, the relative contribution of these two processes to the amount of suction induced is not clear. The objective of this study is to quantify ETr- and transpiration-induced suction by a selected tree species, *Scheffllera heptaphylla*, in silty sand. The relative contribution of transpiration and evaporation to the responses of suction is then explored based on observed differences in transpiration- and ETr-induced suction. In total, 12 test boxes were used for testing, 10 for vegetated soil with different values of Leaf area index (LAI) and Root Area Index (RAI), while two were for bare soil as references. Each box was exposed under an identical atmospheric condition controlled in a plant room for monitoring suction responses over a week. Due to the additional effects of soil evaporation, ET-induced suction could be 3% – 47% higher than transpiration-induced suction, depending on LAI. The significance of evaporation reduced substantially when LAI was higher, as relatively less radiant energy fell on the soil surface for evaporation. For a given LAI, the effects of evaporation were less significant at deeper depths within the root zone. The effects of RAI associated with root-water uptake upon transpiration were the dominant process of ETr affecting the suction responses.

Keywords: Suction, Evapotranspiration, Transpiration, Evaporation, Root Area Index, Leaf Area Index

INTRODUCTION

Evapotranspiration (ETr) is a natural process of the sum of evaporation from soil surface and plant transpiration (Tr) through root-water uptake. The associated changes in soil moisture and soil suction have important implications to the performance of geotechnical infrastructure (Hemmati et al. 2012). This includes water storage capacity and water balance in vegetated landfill covers (Rianna et al. 2014), as well as differential settlement of road/rail embankments induced by plant root-water uptake in the vicinity (Fatahi et al. 2010). It should be noted that suction has been generally recognised to be one of the stress-state variables that governs the behaviour of unsaturated soils (Coleman 1962). It is thus vital to understand the response of soil suction when evaluating engineering behaviour of vegetated soils.

Some studies have been conducted to quantify the partitioning of plant transpiration and soil evaporation for a given ETr (Ritchie 1972; Tratch et al. 1995). Based on the measurements of transpiration, evaporation and ETr, several semi-empirical equations were proposed (Ritchie 1972; Tratch et al. 1995) to partition ETr into these two components through some plant properties such as Leaf Area Index (LAI; a dimensionless index defining the ratio of total one-sided green leaf area to projected area of an individual plant on the soil surface in plan). However, the addition rule may not apply to partition ETr-induced suction into those induced by each individual process of evaporation and transpiration. This is because both the processes are non-linear and are a direct function of suction (Wilson et al. 1994; Feddes et al. 1978; Cui et al. 2013). Also, in addition to LAI, Root area index (RAI; a dimensionless index normalising total root surface area for a given root depth by plan cross-section area of soil) is known to influence soil moisture/suction profiles (López et al. 2001; Zhu and Zhang, 2015). RAI signifies the ability of water uptake by fine roots within the root zone. Compared with other ratios such as Root Length Density (RLD; root length of unit soil volume; Hamblin and Tennant 1987), RAI is considered to be a simplified index. López et al. (2001) correlated RAI and RLD of *Quercus ilex* with soil moisture, and the comparisons suggested that RAI was a more relevant parameter to reflect root-water uptake. A recent study reported by Zhu and Zhang (2015) has also shown that the distribution of RAI within a root zone has direct and significant influence on the magnitude and distribution of induced suction. It should be noted that both LAI and RAI are plant properties, which could be affected by growing conditions.

Although there are various studies focusing on the effects of evaporation on induced suction in bare soil (Wilson et al. 1994; Smits et al. 2011; Song et al. 2013), experimental studies are relatively rare for studying the effects of ETr and transpiration on suction induced in vegetated soil. Improved understanding of plant-induced suction would be useful for calibrating some existing partition equations.

In this study, a laboratory testing programme was designed and conducted to quantify the magnitude and distribution of suction induced by ETr and transpiration of a selected tree species, S. *heptaphylla*, in silty sand. In addition, the effects of plant parameters (such as RAI and LAI) on transpiration- and ETr-induced suction were also explored. Based on the test results, any observed differences between ETr- and transpiration-induced suction were discussed to explore the relative contribution of evaporation and transpiration to suction, in relation to the plant properties, LAI and RAI.

MATERIALS AND METHODS

Test plan

In this study, two series of tests were conducted. The first test series was intended to measure transpiration and also quantify the associated induced suction in soil vegetated with a selected tree species. A tree species, *S. heptaphylla*, which is commonly found in many parts of Asia (Hau and Corlett 2003) was chosen for investigation. In order to explore any effects of plant variability, suction induced by five tree individuals having a similar age but five different LAIs of 2.3, 2.9, 3.9, 4.2 and 4.6 were measured. These five tree individuals were transplanted in test boxes designated as, T1_Tr, T2_Tr, T3_Tr, T4_Tr and T5_Tr, respectively. The aim of the second test series was to measure ETr-induced suction. Another five tree individuals with a similar range of LAIs (test boxes named, T1_ETr T2_ETr, T3_ETr, T4_ETr and T5_ETr) as those tested in the first series were used for testing. The root depth of the ten tree individuals was found to vary between 105 and 130 mm. It was determined that the root growth rate of *Schefflera heptaphylla* at this age was 1–3 mm/week. For the average root depth of 100 mm, this is equivalent to 1% to 3% increase in root length. Thus, it is reasonable to assume that any effect of such limited root growth on suction response is negligible. Testing conditions for all 12 test boxes are summarized in Table 1. For comparison, one pot of bare soil with its surface covered (denoted as box B) and one pot uncovered (denoted as box B_E) were also tested.

Test box and instrumentation

Figure 1 shows the schematic setup of a vegetated test box. Each box has a cross section area of 300 mm x 300 mm and a depth of 350 mm. Soil was compacted in each box and a tree individual was transplanted at the centre. Side boundaries were impermeable while the bottom boundary was subjected to drainage through holes (9 holes) present at the bottom of test box. Top boundary is subjected to a controlled atmospheric condition. Air temperature, radiant energy and relative humidity were maintained at 22.3±1^{o}C, 7.1±1 MJ/m^{2}/d and 53±7%, respectively. Four tensiometers at 30, 80, 140 and 210 mm depths were installed at 10 mm away from the main tree stem as shown in Fig 1(b). Of the four tensiometers, only two were installed within the known root depth. For the given root depth of about 100 mm, installing too many tensiometers would, undesirably, cause severe disturbance to not only the soil but also the root system including its growth. The decision to install the tensiometer at 80 mm depth within the root zone aimed to capture the suction response where peak RAI (discussed later) is generally found in the ten tree individuals. It should be noted that the measurement range of suction is limited by water cavitation in a tensiometer when negative pore-water pressure in soil approaches 80 – 90 kPa (Fredlund and Rahardjo 1993).

In order to simulate plant photosynthesis, a white fluorescent lamp that emits a waveband between 400 and 700 nm (known as photosynthetically active radiation) was mounted on the top of each box. Radiant energy (MJ/m^2/d) received on soil surface, both within and outside the tree canopy (Fig. 1 (a)), was measured using quantum sensors (LI-COR 1991). Each quantum sensor has a photodiode, which is a semi-conductor device that could convert incident light to voltage. After calibration, the voltage recorded would be related to photon flux density (PPF) (μmol/m^2/s). Based on the Planck relationship, the PPF can then be converted to radiant energy, depending on the waveband of the source of incident light. It was found that the radiant energy was constant at 7±1 MJ/m^2/d. Each test box was placed on top of a weighing machine (Model number CG-12K, Vibra Ltd.) for monitoring any mass change during testing. The accuracy of the weighing machine is ± 1 g. The test conditions for all 12 boxes are summarized in Table 1.

Soil properties and preparation of test box

Completely decomposed granite (CDG), which is commonly found in Hong Kong, was selected for testing in this study. Based on measured Atterberg limit and particle-size distribution, CDG is classified as silty sand (SM) according to the Unified Soil Classification System (USCS). Figure 2 shows drying soil water retention curve (SWRC) of CDG soil measured using the transient state method described by Ng and Leung (2012). It can be observed that volumetric water content (θ) of CDG soil reduces gradually from its initial saturated value of 35% after reaching an air entry value of about 3 kPa. At suction of around 80 kPa, θ was reduced to around 9%. The volumetric field capacity of CDG was found to be 16% – 19%, which corresponds to the range of suction (ψ_{fc}; defined as the suction corresponding to measured volumetric field capacity of soil) 15 – 24 kPa. Other index properties of CDG are described in detail in Ng et al. (2013*a*).

In each test box, silty sand was compacted to a depth of 280 mm with a targeted dry density of 1496 kg/m^3 (i.e., equivalent to 80% of the maximum dry density) and gravimetric water content of 12% using the under-compaction method (Ladd 1978). It was found that by using this method, a reasonable uniform dry density profile can be obtained and the maximum deviation from the targeted value was less than 2% along the box depth (Ng et al. 2013*b*).

Test procedures

For the first test series, the bare box (B) and the five vegetated boxes T1_Tr, T2_Tr, T3_Tr, T4_Tr and T5_Tr were subjected to a two-stage test. The first stage was to pond each box until (i) suctions at all four depths decreased to 0 kPa and (ii) percolation through the drainage holes at the box base was observed. Distilled water was used. Then, the second stage was to expose each box in the atmospheric controlled plant room. In order to quantify the effects of tree transpiration on suction responses only, the entire bare soil surface of each vegetated box was covered with a laminated plastic sheet to minimise soil evaporation (see Fig. 1). Upon drying process, any mass loss of each vegetated box (i.e., soil moisture transpired) was monitored continuously by the balance every 24 hours. The measured change of water mass (in g/d) was then converted to water volume (in ml/d) through water density (1 g/ml). The error associated with each measurement would be equal to the root-mean-square error, which is 1.41 ml/d. In fact, error of water transpired/evapotranspired (1.41 ml/d) is less than 1.5% of the maximum rates of ETr and Tr (i.e., 108 and 99 ml/d, respectively as mentioned later) in this laboratory study. The error is thus considered to be negligible. This measurement method assumed that the amount of water transpired was constant within each day and that water consumed for tree photosynthesis was ignored. In fact, the volume of water used for photosynthesis is generally less than 2% (Salisbury and Ross 1992). Any transpiration-induced suctions were recorded by the four tensiometers. Each test was stopped when any tensiometer registered a value close to 80 kPa, which is the limit of the measurement range. The drainage holes at the bottom of all these boxes remained open during the monitoring period.

Similar test procedures were adopted for the second series. The other bare box B_E and the five boxes (T1_ETr, T2_ETr, T3_ETr, T4_ETr and T5_ETr) where the bare soil surface of each box was exposed (i.e., no surface cover). In this case, suction recorded by each tensiometer in the five vegetated boxes was induced by ETr, while any mass loss of each box was attributed to the loss of soil moisture transpired by the tree individual and that evaporated from bare surface.

After testing, RAI distribution along depth of each vegetated test box was measured by using an image analysis conducted by an open source program, Image J (Rasband 2011). The root system of each tree individual was removed from the test box. This was achieved by carefully excavating the entire soil-root ball. Then, roots were separated from the surrounding soil using a specially designed root washer (Smucker et al. 1982), and the roots were refrigerated (at 4-6°C) before conducting image analysis using Image J. During an image analysis, the entire branch of roots was clamped and high-resolution images were taken around 360° and then converted to binary image. These images were superimposed to generate a single picture in three-dimensional space, which was then discretized into grids. The area in each grid containing roots was determined in form of pixel size and was converted to length dimension (in mm^2) by using a calibration factor. Finally, RAI at any depth within root zone can be determined by normalizing the total surface area of roots in all grids at a given depth by the planar cross sectional area of soil. The RAI is defined as the circular area (in mm^2) with a diameter representing the largest lateral spread of roots in that grid. In this study, RAI was discretized at intervals of 10 mm. The reason to provide such a discretized RAI is to more clearly determine the distribution of root surface area, which is shown to be important for interpreting suction (López et al. 2000; Zhu and Zhang 2015; Leung et al. 2015; Garg et al. 2015; Garg and Ng 2015). It should be noted that the calculation of RAI contains a blanket error of 5% that covers the errors caused during image processing (Rasband 2011; Mikulka et al. 2011), including less accurate (i) detection of boundaries of an object that has complex shape (like the root system in this study) and (ii) calculation of pixel size (i.e., area of roots). This measurement method of RAI may be applicable for other plant species, as long as an intact root system could be retrieved from the soil. For larger vegetation, however, collection of root samples from the field should be executed with great care. This is because any loss of roots might affect the evaluation of RAI during the excavation of root system.

INTERPRETATION OF TEST RESULTS

Observed RAI profiles

Figure 3(a) shows the comparison of the distributions of RAI along depth for the five tree individuals tested in the boxes T1_Tr, T2_Tr, T3_Tr, T4_Tr, and T5_Tr. For box T1_Tr, there is an evident increase in RAI from 0.14 to 0.55 at depths ranging from 70 to 80 mm. On the contrary, a substantial decrease of RAI is observed below this particular depth range. For the tree individuals tested in boxes T1_Tr, T2_Tr and T3_Tr, it can be seen that the RAI profiles are rather similar to each other, given the constant blanket error of 5%. However, the magnitude of RAI of the other two tree individuals in boxes T4_Tr and T5_Tr are remarkably larger at all depths. It is found that their peak RAIs range from 0.9 to 1.1, which is 63% higher than the peak value (0.45 – 0.55) found in the boxes T1_Tr, T2_Tr and T3_Tr. This is likely because the tree individuals in boxes T4_Tr and T5_Tr have much higher LAIs (4.2 and 4.6, respectively), which allowed more radiant energy interception for photosynthesis and thus led to better root growth (Ross 1975; Strebeyko 2000).

For the measurements made from the other five boxes tested in the second series (T1_ETr, T2_ETr, T3_ETr, T4_ETr and T5_ETr), the shape of RAI profiles is found to be largely similar (see Fig. 3(b)). However, it can be generally seen that for the same given LAI, the magnitude of RAI of tree individuals subjected to ETr in the second test series was 5% to 15% higher than that to only transpiration in the first series (see also Fig. 3(a)) because of the natural variability of the tree species.

Observed relationships between induced suction and the rates of transpiration and ETr

Figure 4(a) compares the measured suction at 80 mm depth between the bare box B and the four vegetated boxes T1_Tr, T1_ETr, T5_Tr and T5_ETr. Measured rates of transpiration and ETr from each vegetated box are shown in Fig. 4(b). For the bare soil that was covered with plastic sheet (box B), suction is found to remain almost constant at 3 kPa throughout the test (Fig. 4(a)), as expected. In contrast, suctions recorded in all vegetated boxes showed substantial increases. For the box T1_Tr, the suction increased gradually from 2 to 21 kPa, while the corresponding transpiration rate remained almost unchanged at about 45 ml/d (Fig. 4(b)). This suggests that within the testing period, the suction had not yet reached the expected range of ψ_{fc}. This means that the induced suction was not the result of water stress (refers to the phenomenon when capillary action in soil is significant to retain water and hence to suppress root-water uptake by plants; Feddes et al. 1978; van Genuchten 1987). For the tree individual having a similar LAI of

2.3 but subjected to ETr (i.e., box T1_ETr), suction also developed, but the magnitude (21 kPa) at the end of the test was 47% higher due to the additional effects of evaporation. Because of such soil evaporation, the measured ETr rate (56 ml/d; Fig. 4(b)) was higher than the transpiration rate.

For the tree individuals that had a higher LAI of 4.6 (i.e., boxes T5_Tr and T5_ETr), the measured increases in suction were much more significant than the cases with the lower LAI. At the end of each test, the peak suctions induced by transpiration (56 kPa) and ETr (61 kPa) were 166% and 96% higher, respectively (Fig. 4 (a)). This is because a tree individual having a higher LAI generally has larger leaf surface area for more radiant energy interception, and hence greater root-water uptake, to take place. It should be noted that based on Penman equation (Penman 1948), the amount of evaporation of a vegetated soil is governed by not only RH gradient, but also the amount of radiation received at the soil surface. Since the RH was maintained constant in the plant room in our study, the factor that controlled the amount of evaporation would thus be the percentage of radiant energy being intercepted by tree leaves, which is a function of LAI.

As suction developed in the box T5_Tr, the measured rate of transpiration remained constant (i.e., 99 ml/d) in the first four days, but it then decreased substantially thereafter (Fig. 4(b)). Similar trends were observed for the box T5_ETr, although the magnitude of induced suction (Fig. 4(a)) and ETr rate (Fig. 4(b)) were noticeably higher due to the additional effects of soil evaporation. It can be identified that the values of suction corresponding to the onset of the reduction of transpiration rate (i.e., ψ_{fc}) was about 32 kPa. This is, however, at least 33% higher than that of the bare soil (i.e., 15 – 24 kPa). .

Relative contribution of transpiration and evaporation to induced suction

Figure 5 compares the measured vertical distributions of suction induced by the vegetated boxes

T1_Tr and T1_ETr and the two bare boxes B and B_E after one week of testing. It can be seen that the initial suction distributions of all four boxes were fairly close. The observed small difference was apparent as it was within the measurement error of a tensiometer (±1 kPa). After drying for one week, there were marginal increases in suction in the bare box B. Although the bare soil surface was covered to prevent evaporation, the observed response was the consequence of suction redistribution. It can be seen that the measured distribution of suction in the bare soil was fairly uniform, indicating a unit-gradient downward flow. In contrast, the peak suction induced by surface evaporation at 30 mm depth in another bare box B_E (16 kPa) was more than four times higher than that in the box B (~4 kPa). The suction induced in shallower depths in box B_E was higher than those in deeper depths because the hydraulic gradient established at the soil-atmosphere interface during surface evaporation was relatively higher.

For both the vegetated boxes, the measured suction increases were found to be much greater than the two bare boxes because of the additional effects of tree transpiration and ETr. As revealed in Fig. 4 (b), about 324 and 388 ml of the volume of soil moisture were transpired and evapotranspired in boxes T1_Tr and T1_ETr in one week, respectively. This is equivalent to the losses of 4.6% and 6% of average θ, according to the SWRC shown in Fig. 2. When comparing the two vegetated soil, suctions induced in the box T1_ETr at 30 mm (28 kPa) and 80 mm (31 kPa) depth were 52% and 47% higher than those recorded in box T1_Tr, respectively. The observed difference is attributed to the additional loss of soil moisture due to evaporation (i.e., the difference between total water evapo-transpired and transpired is 64 ml as depicted in Fig. 4 (b); equivalent to the loss of 1.4% of average θ). However, it should be pointed out that the observed difference of suction between these two boxes could also be partially due to the different values of RAI. Within the root zone, it can be seen in Fig. 5 that the transpiration-induced suctions in box T1_Tr at 30 and 80 mm depths were fairly uniform at about

20 kPa, probably because RAI at these two depths were comparable for this particular tree individual (Fig. 3(a)). On the contrary, the ETr-induced suction at 80 mm depth in box T1_ETr (31 kPa) was higher than that at 30 mm depth by 11%. This may be because of higher RAI (by 66%) at 80 mm depth than at 30 mm depth for this tree individual (T1_ETr) (see Fig. 3(b)). Below the root zone where RAI was zero, substantial amount of suction was induced in test boxes subjected to both transpiration and ETr. This means that the presence of plant roots did not only lead to the re-distribution of suction in the root zone, but also at some depths below after subjected to one week of drying.

Moreover, it is interesting to observe that the shape of the induced suction profile of the vegetated box T1_ETr was distinctively different from that of the bare box B_E. While the peak suction occurred at 30 mm depth in the bare box due to surface evaporation, the peak value is identified at the deeper depth of 80 mm depth in T1_ETr. This suggests that as compared to evaporation, it was likely that transpiration was a more dominant process in the vegetated box T1_ETr as the responses of suction are found to be more dependent upon the magnitude of RAI.

DISCUSSION

In order to explore any effects of variability of the selected tree species on suction responses, the peak suctions induced by the ten tree individuals at 30 and 80 mm depth are related with LAI in Fig. 6(a). It is evident that suctions at 30 mm depth induced by either Tr or ETr increased with an increasing LAI due to the increasing radiant energy interception. It can be seen that in general, the difference between ETr- and transpiration-induced suction at both depths reduced with an increase in LAI. As LAI increased from 2.3 to 4.6, the percentage of radiant energy interception increased from 15±4% to 54±6% for transpiration, while simultaneously the remaining radiant energy fallen on the soil surface for evaporation reduced from 85% to 46%. However, it should be noted that the reduced evaporation due to increase in LAI might be more evident in the laboratory pot experiments than in the field. Rey et al. (2008) showed that intercepted energy for a species that has similar canopy architecture to those tested in this study can be 5% to 10% higher in the field than in laboratory pots, depending on LAI. This is because larger surface area of soil beneath canopy is exposed to diffuse radiation in field than in test pots of limited size.

It can be stated from current laboratory study that the effects of evaporation became insignificant when LAI reached certain critical values, even though the amount of radiant energy fallen on the soil surface for evaporation was as high as 46% of the applied radiant energy for the case with the highest LAI of 4.6. Any such critical LAI, however, is found to be not the same at the depths of 30 mm (> 4.6) and 80 mm (3.9). Such inconsistency suggests that LAI alone is not sufficient to explain the different suction responses observed at these two depths.

When relating with RAI (Fig. 6(b)), the induced suction showed also an increasing trend with this tree property. This is because a higher RAI means having a greater root surface area for tree root-water uptake. For the given range of RAI, suction induced by ETr at 30 mm depth is found to be always higher than that by transpiration, whereas there was no discernible difference between ETr- and transpiration-induced suction at 80 mm depth. This highlights that the effects of evaporation at the shallower depth of 30 mm were more significant. This is because soil evaporation is associated with relative humidity gradient across the soil-atmosphere interface, and its effect on suction is thus anticipated to be greater in shallower depths. On the contrary, the effects of evaporation appeared not to be significant enough to affect the suction response at 80 mm depth, as compared to the effects of RAI associated with root-water uptake.

SUMMARY AND CONCLUSIONS

This study interprets a set of laboratory test data containing results from 12 test boxes. These tests aimed to quantify transpiration, evaporation and evapotranspiration and their effects on suction induced in silty sand vegetated with S. *heptaphylla*. The measured induced suctions were interpreted in relation to the percentage of radiant energy intercepted by tree leaves, as well as some key tree properties including LAI and RAI. The relative contribution of transpiration, evaporation and evapotranspiration to the magnitude and distribution of suction were discussed.

As compared to the suction induced by evaporation in bare soil (4 kPa), the ETr- and transpiration-induced suction is found to be 312% and 250% higher after one week of monitoring, depending on LAI and RAI of tree individuals. It is revealed that as LAI increased from 2.3 to 4.6, the magnitude of both ETr- and transpiration-induced suction increased significantly because of the increasing percentage of radiant energy interception by tree leaves from 15% to 54%. It is evident that the contribution of evaporation to the magnitude of suction reduced substantially when tree individual has a higher LAI. This is because as LAI increases, the radiant energy fallen on the bare surface for evaporation decreased simultaneously, even though the percentage of energy interception was as high as 46% for the case of the highest LAI of 4.6.

The test dataset also showed that the presence of tree and its ETr have significant effects on the distribution of suction with depth, especially within the tree root zone. The peak induced suction by ETr did not occur at shallower depth of 30 mm (as observed from the bare soil when subjected to evaporation), but at a much deeper depth of 80 mm where the maximum RAI was found. For a given range of RAI (0.3 – 1.1) investigated in this study, suctions induced by ETr at 30 mm depth were higher than that by transpiration, but there was little difference between them at 80 mm depth. This suggests that although the effect of evaporation did influence the suction induced by ETr at relatively shallower depth of 30 mm. However, given the short period of measurement, it was not significant enough to affect the response at 80 mm depth.

This laboratory study has demonstrated the importance of considering both LAI and RAI to determine the contribution of transpiration and ETr to induced suction. This has not been adequately captured by existing simplified equations, which generally overlook the effects of RAI that would affect suction directly. The test data presented in this paper can be used to calibrate these equations for better prediction of suction magnitude due to the partitioning of transpiration and ETr for a given LAI and RAI in the future.

ACKNOWLEDGEMENTS

The authors would like to acknowledge research grant (2012CB719805) from the National Basic Research Program (973 Program) provided by the Ministry of Science and Technology of the People's Republic of China and research grant (HKUST6/CRF/12R) provided by the Research Grants Council (RGC) of the Hong Kong Special Administrative Region and also financial support from Hong Kong PhD Fellowship Scheme (HKPFS) for the first author. The second author would also like to acknowledge the research grant provided by the EU Marie Curie Career Integration Grant (PICG14-GA-2013-631541) under the project "BioEPIC slope", as well as the research travel fund supported by the Northern Research Partnership (NRP).

REFERENCES

Coleman, J. D. 1962. Stress-strain relations for partially saturated soils. Géotechnique, **12**(4), 348-350.

Cui, Y. J., Ta, A. N., Hemmati, S., Tang, A. M. and Gatmiri, B. 2013. Experimental and numerical investigation of soil-atmosphere interaction. Engineering Geology, **165**, 20-28.

Garg, A., Coo, J.L. and Ng, C.W.W. 2015. Field study on influence of root characteristics on suction distributions in slopes vegetated with Cynodon dactylon and Schefflera heptaphylla.

Earth surface processes and landforms. In press. DOI: 10.1002/esp.3743

Garg, A. and Ng, C.W.W. 2015. Investigation of soil density effect on suction induced by root water uptake. Journal of Plant Nutrition and Soil Science (In press)

Fatahi, B., Khabbaz, H. and Indraratna, B. 2010. Bioengineering ground improvement considering root water uptake model. Ecological Engineering **36**(2), 222-229.

Feddes, R. A., Kowalik, P.J. and Zaradny, H. 1978. Simulation of field water use and crop yield. Centre for Agricultural Publishing and Documentation.

Fredlund, D. G., and Rahardjo, H. 1993. Soil mechanics for unsaturated soils. John Wiley & Sons, New York

Grayston, S. J., Vaughan, D. and Jones, D. 1997. Rhizosphere carbon flow in trees, in comparison with annual plants: the importance of root exudation and its impact on microbial activity and nutrient availability. Applied soil Ecology, **5**(1), 29-56.

Hamblin, A. P. and Tennant, D. 1987. Root length density and water uptake in cereals and grain legumes: how well are they correlated. Crop and Pasture Science, **38**(3), 513-527

Hau B. C. and Corlett, R. T. 2003. Factors affecting the early survival and growth of native tree seedlings planted on a degraded hillside grassland in Hong Kong, China. Restoration Ecology **11**, 483-488.

Hemmati, S., Gatmiri, B., Cui, Y. J. and Vincent, M. 2012. Thermo-hydro-mechanical modelling of soil settlements induced by soil-vegetation-atmosphere interactions. Engineering Geology, **139**, 1-16.

Ladd, R.S. 1977. Specimen preparation and cyclic stability of sands. Journal of Geotechnical Engineering Division **103**(6): 535-547.

Leung, A.K., Garg, A., Ng, C.W.W, and Hau, B.C.H .2015. Effects of the roots of Cynodon dactylon and Schefflera heptaphylla on water infiltration rate and soil hydraulic conductivity.

Hydrological Processes. In press. DOI: 10.1002/hyp.10452

LI-COR. 1991. LI-COR Radiation Measurement Instruments Lincoln, Nebraska, USA

López, B., Sabaté, S. and Gracia, C. A. 2001. Vertical distribution of fine root density, length density, area index and mean diameter in a Quercus ilex forest.Tree physiology, **21**(8), 555-560.

Mikulka, J., Gescheidtová, E. and Bartušek, K. 2011. Evaluation of errors in manual image processing. In Proceedings of Progress In Electromagnetic Resource Symposium, 84-86, Suzhou, China

Ng, C. W. W. and Leung, A. K. 2012. Measurements of drying and wetting permeability functions using a new stress-controllable soil column. Journal of Geotechnical and Geoenvironmental Engineering, **138**(1), 58-68.

Ng, C.W.W., Woon, K. X., Leung, A. K. and Chu, L. M 2013a. Experimental investigation of induced suction distributions in a grass-covered soil. Ecological Engineering **52**:219-223.

Ng, C. W. W., Leung, A. K. and Woon, K.X. 2013b. Effects of soil density on grass-induced suction distributions in compacted soil subjected to rainfall. Canadian Geotechnical Journal, **51**(3): 311-321.

Penman, H. L. 1948. Natural evaporation from open water, bare soil and grass. Proceedings of the Royal Society of London. Series A. Mathematical and Physical Sciences, **193**(1032), 120-145.

Rey, H., Dauzat, J., Chenu, K., Barczi, J. F., Dosio, G. A. and Lecoeur, J. 2008. Using a 3-D virtual sunflower to simulate light capture at organ, plant and plot levels: contribution of organ interception, impact of heliotropism and analysis of genotypic differences. Annals of botany, **101**(8), 1139-1152

Rianna, G., Pagano, L. and Urciuoli, G. 2014. Investigation of soil-atmosphere interaction in pyroclastic soils. Journal of Hydrology, **510**: 480-492

Ritchie, J.T. 1972. Model for predicting evaporation from a row crop with incomplete cover. Water Resource Research, **8**: 1204–1213

Ross, J. 1975. Radiative transfer in plant communities. Vegetation and the Atmosphere, 1, 13-55.

Salisbury, F. B. and Ross, C. W. 1992. Plant Physiology. 4th. Edn. Belmont, CA. Wadsworth.

Scanlan, C.A. and Hinz, C. 2010. Insight into the processes and effects of root induced changes to soil hydraulic properties. In 19th World Congress of Soil Science, Soil Solutions for a Changing World, Brisbane, Australia, 1–6 August 2010, pp. 41–44

Scholl, P., Leitner, D. and Kammerer, G. 2014. Root induced changes of effective 1D hydraulic properties in a soil column. Plant and Soil. Open Access, http://dx.doi.org/10.1007/s11104-014-2121-x

Smucker, A. J. M., McBurney, S. L. and Srivastava, A. K. 1982. Quantitative separation of roots from compacted soil profiles by the hydropneumatic elutriation system. Agronomy Journal, **74**(3), 500-503.

Song, W. K., Cui, Y. J., Tang, A.M. and Ding, W.Q. 2013. Development of a large-scale environmental chamber for investigating soil water evaporation. ASTM Geotechnical Testing Journal, **36**(6), 847-857.

Strebeyko, P. 2000. Radiant energy utilized in photosynthesis. Photosynthetica, **37**(4), 639-640.

Traoré, O., Groleau-Renaud, V., Plantureux, S., Tubeileh, A. and Boeuf-Tremblay, W. 2000. Effect of root mucilage and modelled root exudates on soil structure. Europe Journal of Soil Science, **51**(4): 575-581.

Tratch, D. J., Wilson, G. W. and Fredlund, D. G. 1995. The Prediction of Moisture Uptake in the Root Zone Due to Transpiration for Problems in Geotechnical Engineering. In 48th Canadian Geotechnical Conference, Vancouver, BC, September (pp. 25-27).

van Genuchten, M. T. 1987. A numerical model for water and solute movement in and below the root zone. United States Department of Agriculture Agricultural Research Service US Salinity Laboratory.

Wilson, G. W., Fredlund, D.G. and Barbour, S.L. 1994. Coupled soil-atmosphere modelling for soil evaporation. Canadian Geotechnical Journal, **31**(2), 151-161.

Zhu, H. and Zhang, L. M. 2015. Evaluating suction profile in a vegetated slope considering uncertainty in transpiration. Computers and Geotechnics, **63**, 112-120

List of Captions

Table 1 A summary of test programme

Figure 1 Typical schematic setup and instrumentation of a tree vegetated test box subjected to transpiration in (a) plan view and (b) cross section view X-X

Figure 2 Measured and fitted drying soil water retention curve of CDG soil

Figure 3 Measured root area index (RAI) profiles for the five tree individuals tested (a) in the first test series, and (b) in the second series

Figure 4 Comparisons of (a) suction (80 mm depth) and (b) Tr or ETr rates between test boxes T1 (LAI = 2.3) and T2 (LAI = 4.6)

Figure 5 Comparison of vertical distributions of suction after one week of drying between bare and vegetated soil

Figure 6 Relationships of peak induced suction within root zones (at 30 and 80 mm depths) of the ten tree individuals with their properties (a) LAI and (b) RAI

Table 1. A summary of test programme

Test box ID	Boundary condition				Tree characteristic		
	Top			Bottom			
	E	Tr	ETr	Drainage	LAI	Peak RAI	Root depth (mm)
B	-	-	-	√	N/A	N/A	N/A
B_E	√	-	-	√			
T1_Tr	-	√	-	√	2.3	0.45	95
T2_Tr	-	√	-	√	2.9	0.50	90
T3_Tr	-	√	-	√	3.9	0.55	100
T4_Tr	-	√	-	√	4.2	0.90	130
T5_Tr	-	√	-	√	4.6	1.10	120
T1_ETr	-	-	√	√	2.2	0.48	100
T2_ETr	-	-	√	√	3.0	0.58	90
T3_ETr	-	-	√	√	3.9	0.65	115
T4_ETr	-	-	√	√	4.1	1.00	120
T5_ETr	-	-	√	√	4.6	1.10	125

Note: *E* denotes Evaporation; *Tr* denotes Transpiration; *ETr* denotes Evapotranspiration; *LAI* denotes Leaf Area Index; and *RAI* denotes Root Area Index;

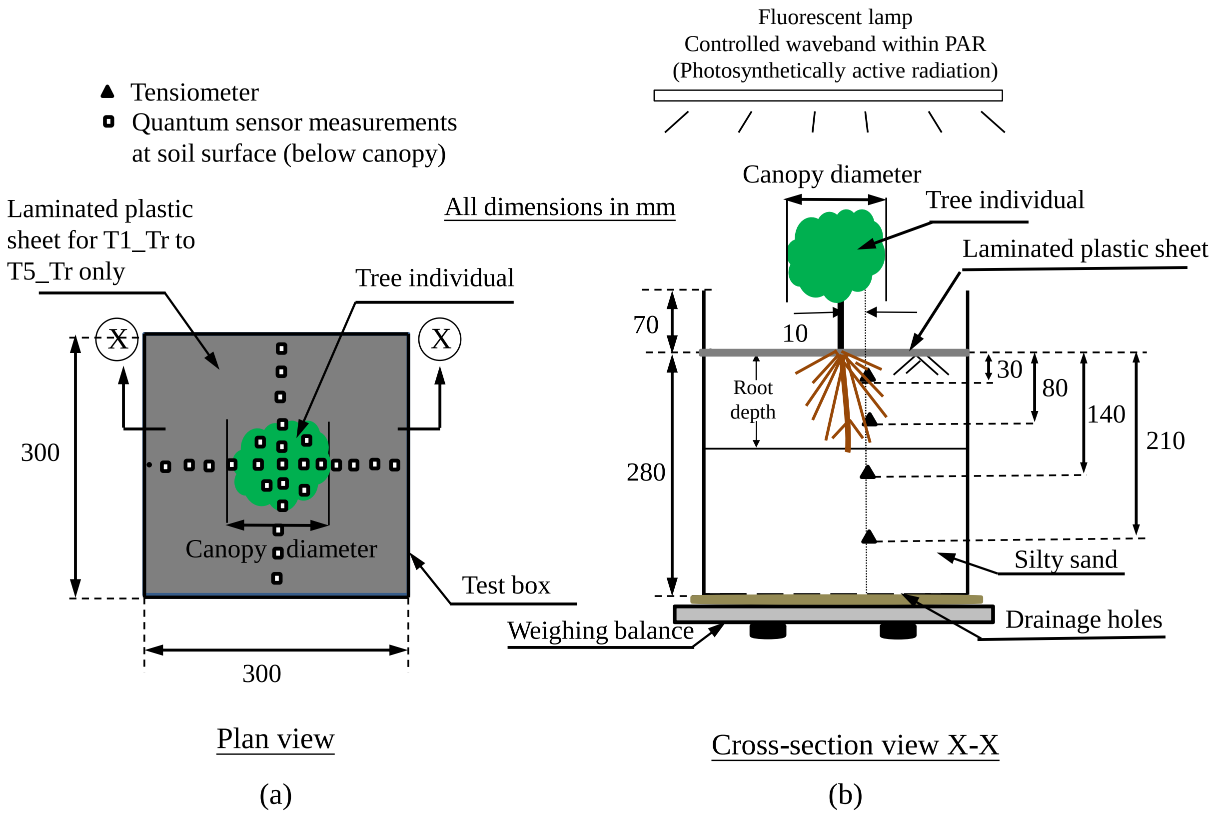


Fig. 1. Typical schematic setup and instrumentation of a tree vegetated test box subjected to transpiration in (a) plan view and (b) cross-section view X-X.

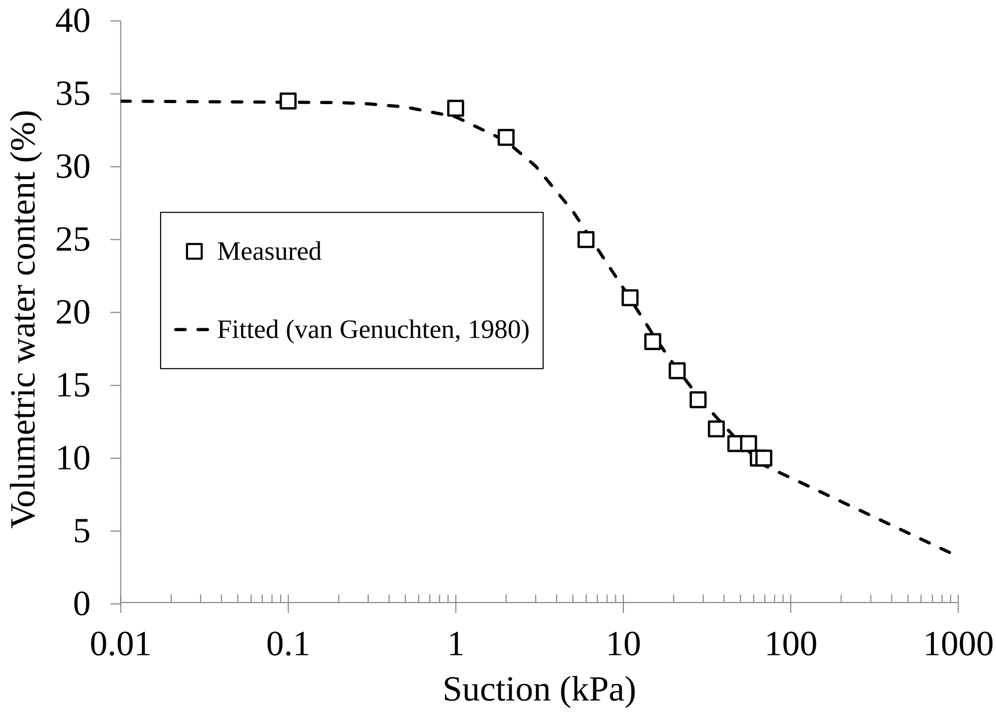
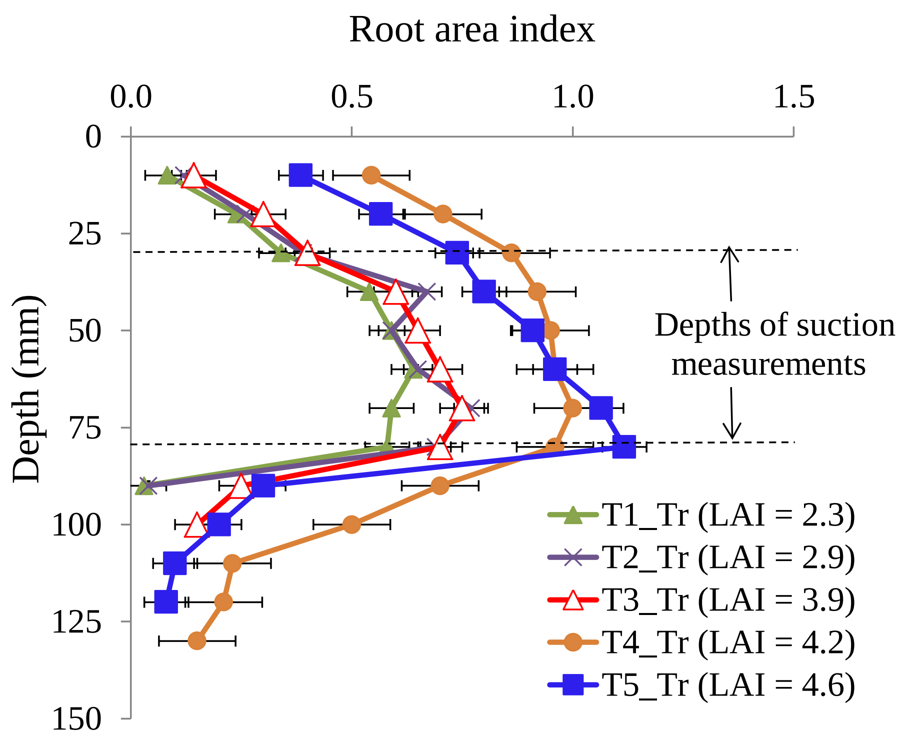
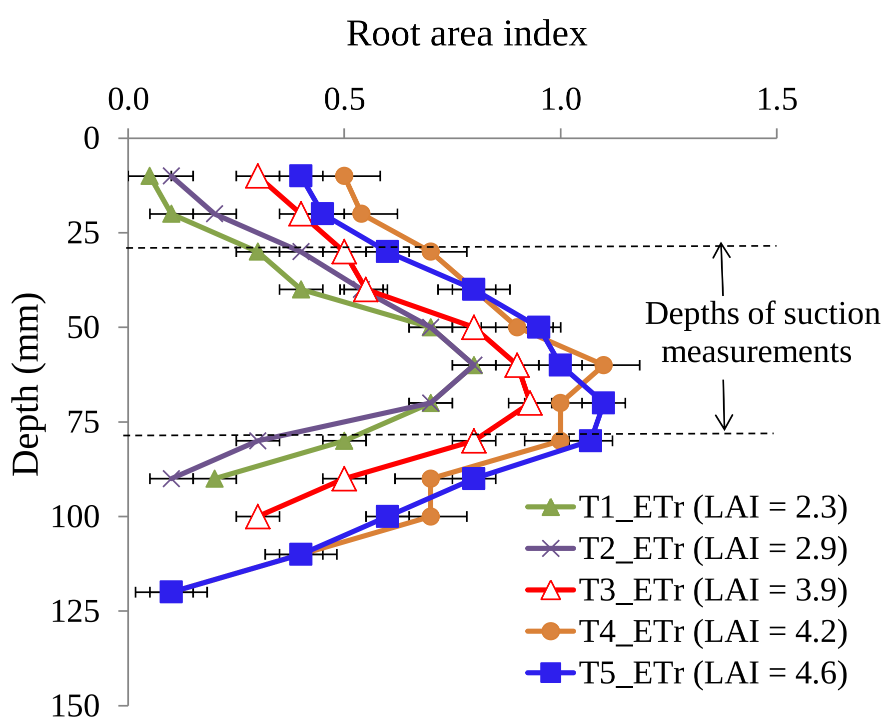


Fig 2. Measured and fitted drying soil water retention curve of CDG soil

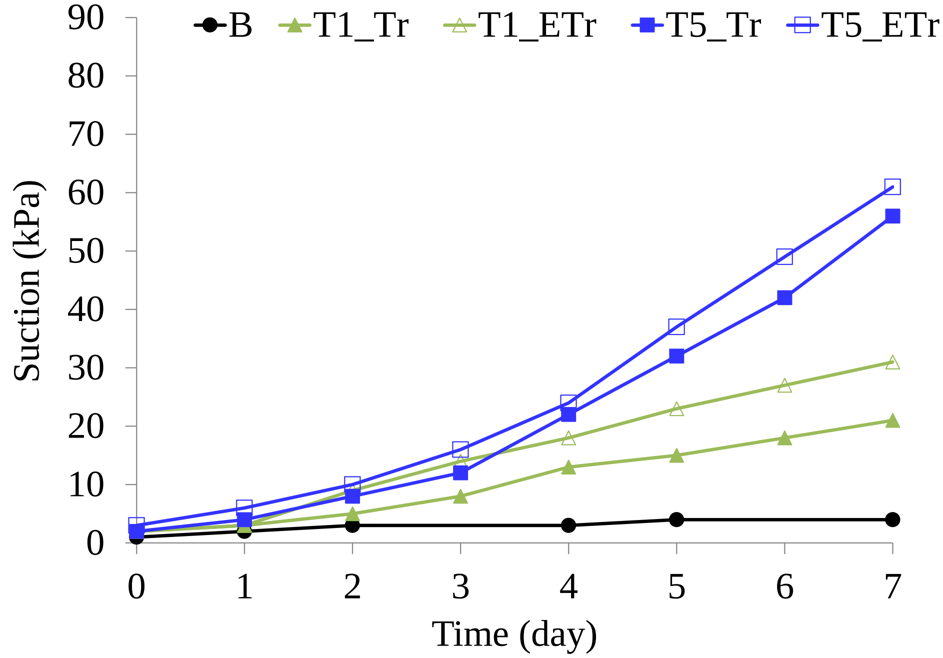


(a)

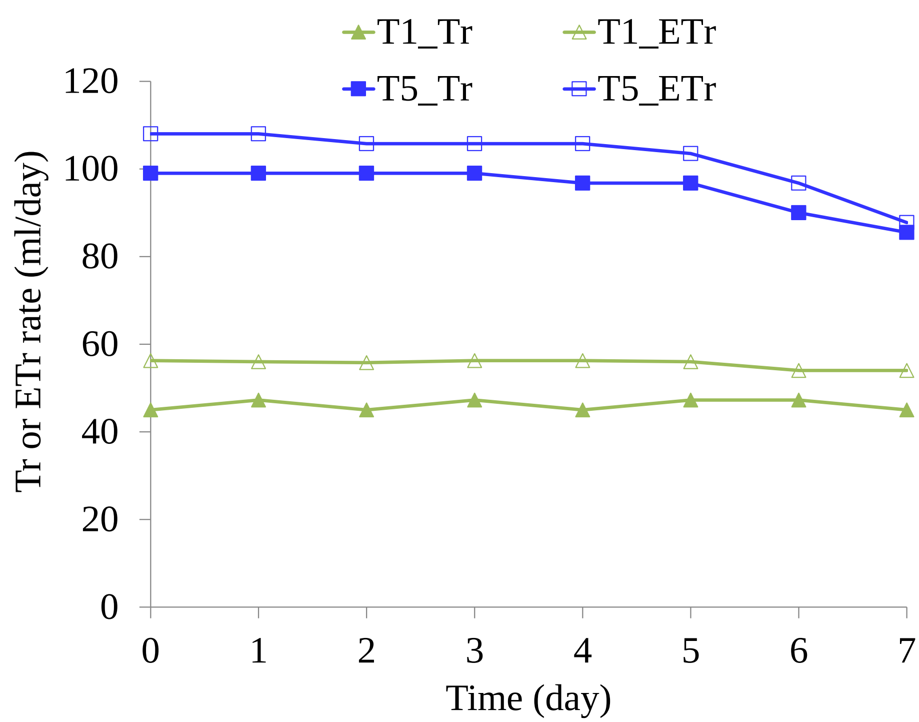


(b)

Fig. 3. Measured root area index (RAI) profiles for the five tree individuals tested (a) in the first test series, and (b) in the second series



(a)



(b)

Fig. 4. Comparisons of (a) suction (80 mm depth) and (b) Tr or ETr rates between test boxes T1 (LAI = 2.3) and T5 (LAI = 4.6)

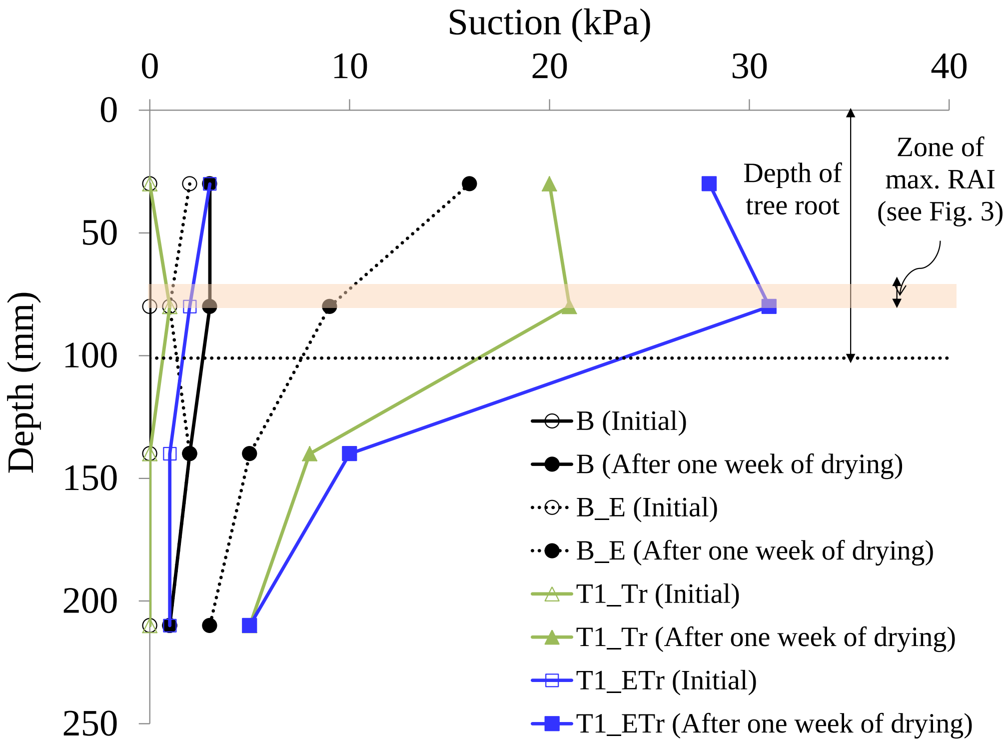
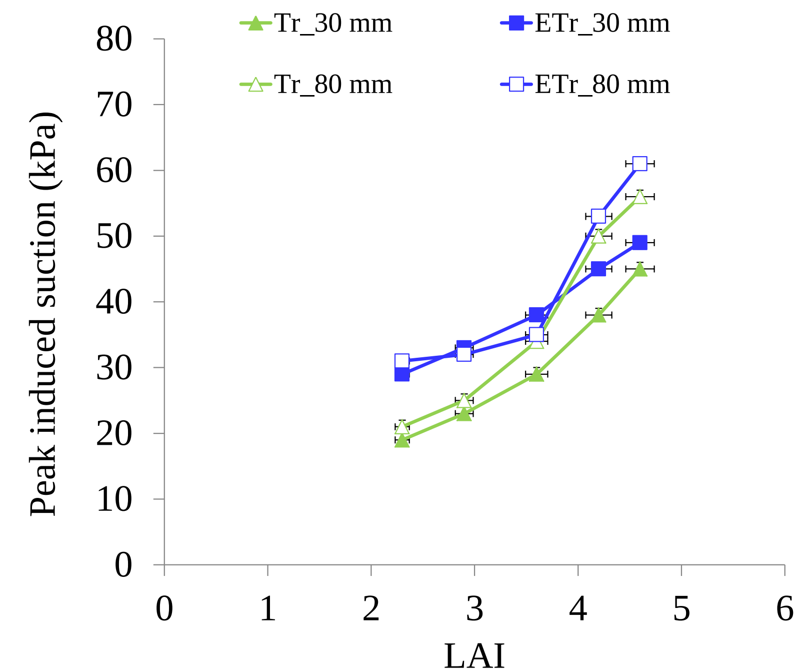
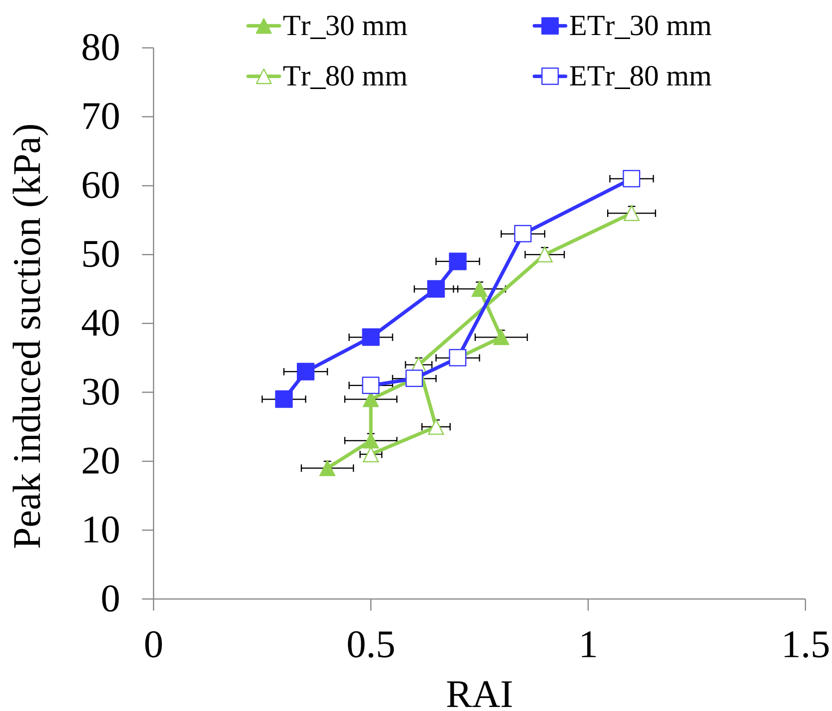


Fig. 5. Comparison of vertical distributions of suction after one week of drying between bare and vegetated soil



(a)



(b)

Fig. 6. Relationships of peak induced suction within root zones (at 30 and 80 mm depths) of the ten tree individuals with their properties (a) LAI and (b) RAI